Chapter 7
Numerical Modeling of Tidal Inlets

7-1. Purpose and Scope

Coastal phenomena such as waves, currents, water levels, flow discharge, water quality, and sediment transport can be numerically simulated at inlets to predict impacts of existing or proposed design alternatives. For example, it may be necessary to maintain or improve inlet characteristics such as water quality, channel navigability, structural integrity, channel shoaling rates, and sediment bypassing strategies for a particular inlet configuration or maintenance plan. By comparing existing coastal processes to those simulated, effects of design plans and operation and maintenance (O&M) practices can be assessed and optimized. The purpose of this chapter is to describe numerical models that have been used to predict these various coastal phenomena at inlets. Section 7-2 presents an overview of various physical processes normally considered in numerical models of tidal inlets. Sections 7-3 through 7-7 discuss different types of numerical models and modeling systems that have been applied in Corps studies and are available to Corps field offices. A brief description of each model is followed by a list of model input and output requirements, example model applications, and an additional bibliography. In Section 7-8, the implementation of numerical models is discussed. This section deals with numerical grid characteristics, grid generation, and calibration and verification of the models. Finally, Section 7-9 discusses engineering use of model results.

7-2. Overview of Physical Processes Considered

The following physical processes are usually considered in numerical modeling of tidal inlets under nonstorm conditions: astronomical tides, winds, short period waves, freshwater flows, and sediment transport. Under hurricane and storm conditions, the effects of storm surge also have to be accounted for (refer to EM 1110-2-1412).

a. Astronomical tides. Tides can be a major forcing mechanism at inlets. Tides are long-period waves, which can be predicted accurately along the open coast using results of harmonic analysis of measured water level fluctuations. Near inlets and in the interior, numerical models must be used for tidal prediction because of the complex interactions between bathymetry, inlet and back-bay geometry, proximity of structures, and interconnection with other inlets. Tides change currents and water levels, which are important for circulation and sediment transport.

b. Winds. Winds induce a change in water level (wind setup) and currents, the magnitude of which depends on wind speed and direction. Water level increases in the direction of the wind. Currents are in the direction of the wind at the surface, but direction and magnitude may vary in the vertical. Wind effects are usually accounted for in either a tidal or a wave-induced current model.

c. Short-period waves. Short-period ocean waves are represented near inlets either by a monochromatic wave (e.g., significant wave) or a wave spectrum. In the first approach, individual waves are characterized by wave height, period, and direction. In the second approach, a wave with a specified height is characterized by the distribution of energy in different frequency (period) and direction bands. Short waves result in changes in water level (wave setup) and wave-induced currents (longshore and rip currents) near inlets which cause not only changes in flow pattern, but also sediment transport. Wave orbital velocities at the bed cause increased shear stresses, resulting in greater sediment transport. Because of the complex transformation processes which take place in the nearshore, short waves are predicted near inlets using numerical models of the monochromatic or spectral type. In either case, the wave characteristics in deeper water are either measured in the field, or obtained from forecast or hindcast performed using a spectral model (e.g., Phase II of WES Wave Information Study (WIS)).

d. Freshwater flows. Freshwater flows into the back-bay system from rivers and creeks influence both flow patterns and salinities. Data on such flows are obtained from agencies such as the U.S. Geological Survey (USGS), state and local water resources agencies, and/or from special gauges installed for the project. These flows have to be specified at the boundaries of the numerical model grid.

e. Sediment transport. Magnitude and direction of inlet sediment transport depend on the processes described in *a* through *d*. Sediment transport at inlets is of major concern to coastal engineers and planners, because its rate and distribution through the inlet affect many processes of engineering concern (e.g., channel shoaling rates, erosion/accretion of interior (bay) and ocean (adjacent) inlet shorelines, stability of structure foundations (jetties, bridge pilings), etc.). Modifications which change the existing transport rates and patterns can disrupt the integrity and viability of a stabilized, navigable inlet. Typically, sediment transport in the back bay is characterized by cohesive materials such as clays, silts, and fine sands, whereas transport in the region offshore of the inlet throat is characterized by noncohesive materials such as sand and shell. Usually, sediment transport models use the results of hydrodynamic models for input.

7-3. Long-Wave Models

a. Lumped parameter models. This type of model gets its name from "lumping" several important variables together, such as discharge or back-bay storage capacity. An example of a lumped parameter model is the Spatially Integrated Numerical Model of Inlet Hydraulics, an inlet-bay hydraulic model (Figure 7-1) developed by Seelig (1977) and Seelig, Harris, and Herchenroder (1977), and available through the U.S. Army Corps of Engineers' (USACE's) Automated Coastal Engineering System (ACES) (Leenknecht, Szuwalski, and Sherlock 1992a, 1992b).

(1) Description. This model can be used to calculate coastal inlet velocities, discharge, and bay surface level as a function of time for a given time-dependent sea level fluctuation. It is applicable to one or two inlets connected to a bay with two sea boundary conditions, although only the one-inlet, one-bay system has been tested in the ACES (Leenknecht, Szuwalski, and Sherlock 1992a). The one-dimensional equation of motion is integrated over the area of the inlet. The resulting momentum equation and continuity equation are solved by marching in time. The model idealizes the inlet-bay geometry and makes several simplifying assumptions, detailed by Seelig, Harris, and Herchenroder (1977) and Leenknecht, Szuwalski, and Sherlock (1992a, 1992b). The model can be used to evaluate inlet velocities, bay water level fluctuations, and discharges caused by tides, storm surge, seiches, and tsunamis. This type of model can be used to take a quick "first look" at several alternatives. The model should be calibrated and preferably verified for a given project before it is used for prediction.

(2) Model requirements. Five general types of information are required for input: general data describing system configuration and temporal data; inlet geometries characterized with cross-section tables and locations; seaward boundary conditions (tabulated records or predicted tides using harmonic constituents); bayside boundary conditions (bay area and shape factor, and other freshwater inflows distinct from inlet contributions); and locations where velocity hydrographs are to be reported from the simulation (Leenknecht, Szuwalski, and Sherlock 1992a). The model should be calibrated (and verified, if possible) using known bay surface elevations and inlet velocity measurements. Three output data files are written, consisting of tabular summaries of grid characteristics, velocity hydrographs at selected cell locations, and elevation and discharge hydrographs for the sea boundary conditions, bay, and inlet(s). Samples of model runs (input and output) are given by Leenknecht, Szuwalski, and Sherlock (1992a).

(3) Example applications. The model has been applied to Pentwater Inlet, Michigan, to study the response of a nontidal Great Lakes inlet to forcing due to seiching of Lake Michigan; a hypothetical harbor to predict tsunami-induced hydraulics; Masonboro Inlet, North Carolina, to determine inlet response to tides (Harris and Bodine 1977); Indian River Inlet, Delaware, to predict the effect of storm surge at a tidal inlet; and Cabin Point Creek, Virginia, to illustrate the effect of adding a second inlet to a one-inlet tidal system.

(4) Bibliography. Seelig (1977) and Seelig, Harris, and Herchenroder (1977) discuss development of the original model. Leenknecht, Szuwalski, and Sherlock (1992a, 1992b) discuss limitations and application of the model within the ACES.

b. One-dimensional models. An example of a one-dimensional (1-D) model is the Dynamic Implicit Numerical Model of One-Dimensional Tidal Flow through Inlets (DYNLET1) (Amein and Kraus 1991). The discussion presented herein has been abbreviated from Amein and Kraus (1991).

(1) Description. DYNLET1 is based on the full one-dimensional shallow-water equations, employing an implicit finite-difference technique. The model is suited for reconnaissance-level studies for most inlets, providing reliable and accurate answers with minimal data entry and grid generation. DYNLET1 predicts flow conditions in channels with varied geometry, and will accept varying friction factors across an inlet channel, geometric data at variable distances across and along an inlet channel, and a variety of boundary conditions. The inlet to be modeled may consist of a single channel connecting the sea to the bay, or it can be a system of interconnected channels, with or without bays. Values of water surface elevation and average velocity are computed at locations across and along inlet channels.

(2) Model requirements. DYNLET1 uses four input files and generates five output files. The inlet is represented by a series of channels, junctions, and nodes. If

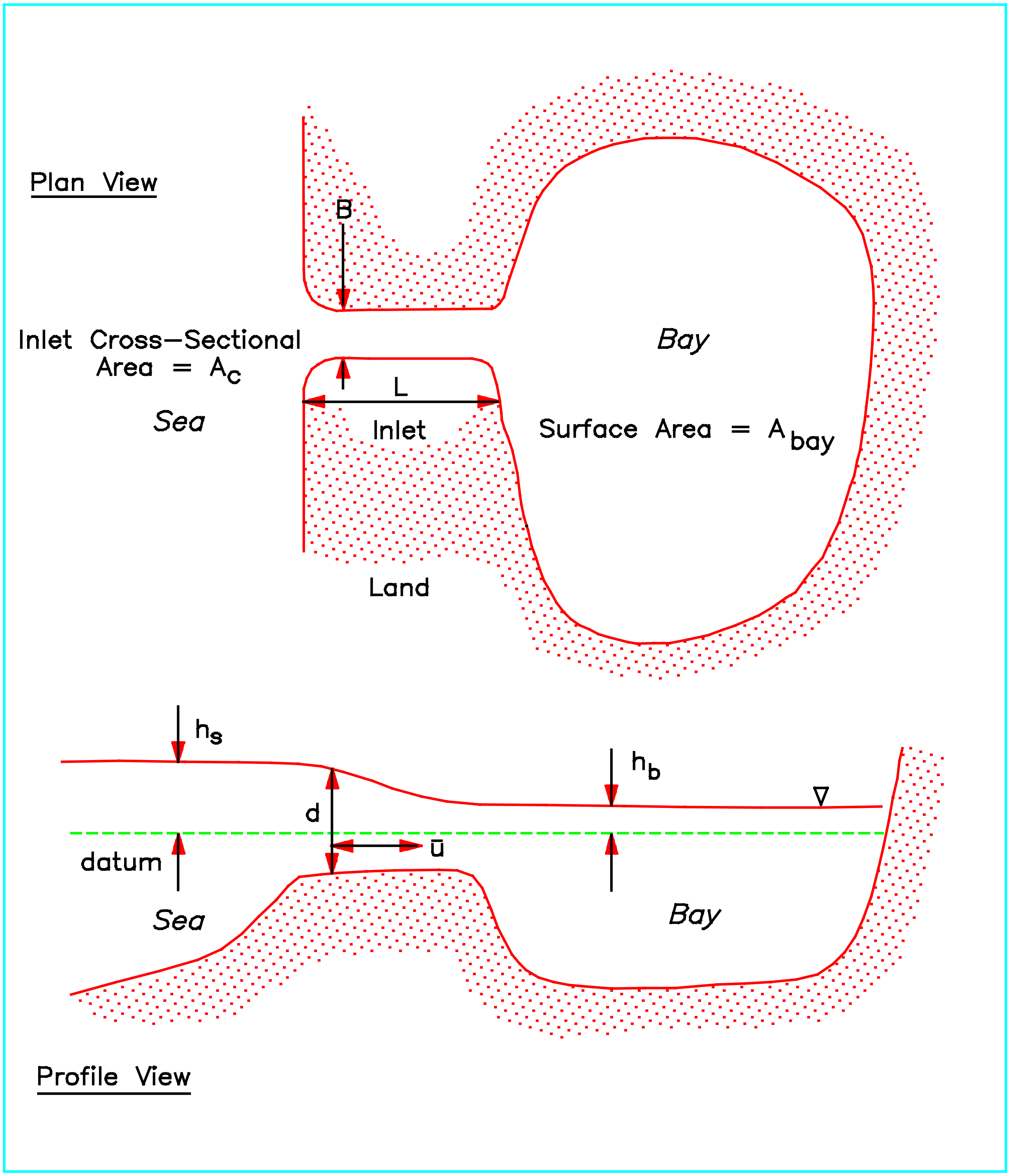

Figure 7-1. Inlet-bay system (Seelig, Harris, and Herchenroder 1977)

two channels meet or a channel branches into two forks, a junction is formed. Each representative cross section in a channel is identified by a node. Input data required include general setup parameters, detailed information on cross-section geometry and boundary resistance, time-dependent boundary data for each external boundary node, tabulated as a function of time, and desired output nodes and parameters. The primary output file includes an echo of the input data, computed values of the volume flow rate, water surface elevations, and average velocity at designated nodes at the specified times. Three other output files contain information that may be used with auxiliary programs, to facilitate evaluation and plotting of the results. The fifth output file contains nodal values of the convective acceleration, temporal acceleration, and pressure gradient normalized by the bottom stress, so that the strengths of these terms relative to that of the friction term can be evaluated.

(3) Example applications. Amein and Kraus (1991) present application and verification of DYNLET1 with two case studies: an inlet which has a system of interconnected channels without a well-defined bay, Masonboro Inlet, North Carolina; and Indian River Inlet, Delaware, an inlet with two well-defined bays that is protected by two jetties at its entrance.

(4) Bibliography. The theory and procedures for operation, application, and verification of DYNLET1 are presented by Amein and Kraus (1991).

c. Link-node model. An example of this type is the DYNTRAN (Dynamic Transport) link-node model of Camp, Dresser, & McKee (Moore and Walton 1984).

(1) Description. In DYNTRAN, the prototype system is represented by a network of nodes and links (Figure 7-2). A node corresponds to a particular reach of the prototype, having a certain volume and surface area. A link represents a channel or other pathway along which water flows from one node to an adjacent node. Each link is characterized by a length, cross-sectional area, and velocity (flow). The DYNTRAN model combines a hydrodynamic model and a transport model. The former solves the one-dimensional momentum equation along the links and applies the continuity equation at the nodes, thereby determining the velocity (flow) in the links, and the elevation at the nodes. The latter solves for mass transport of salt and a nonconservative constituent. DYNTRAN simulates hydrodynamics under the action of tides, freshwater flows, winds, and density gradients. It is simpler than the two- and three-dimensional long-wave models that will be described in the sections that follow. The model may be applied to a project either at the feasibility or design stage. In setting up the link-node system for a particular project, bathymetry, coastline, tidal and other boundary locations, desired degree of resolution, and locations of field gauges should be carefully considered. Because the model assumes the flow in a link is along the direction of the link, links should be oriented to represent known or logically expected flow directions. As a result, the model is well-suited to applications where the flows are well-channeled. It is less applicable to projects where the flows are two-dimensional and the flow directions are not known.

(2) Model requirements. Required model input consists of accurate bathymetric data, information to characterize the links and nodes (Figure 7-2), tidal elevations, freshwater flows, salinity and constituent mass flows as functions of time at the model boundaries, information on wind speed and direction, and initial concentrations. Field measurements of surface elevation, velocity, salinity, and concentration in the interior of the system are required for calibration and verification of the model. As a part of its output, the model “echo prints” the input.

(3) Example applications. DYNTRAN has been applied in several studies for the U.S. Navy (GKY and Associates 1988a, 1988b) to furnish the hydrodynamics to drive a water quality model to determine the fate and transport of organotin from Navy ships in Navy harbors. These harbors include Charleston, Mayport, Pearl Harbor, Everett, and Bremerton. The model was applied in a reconnaissance study performed for the U.S. Army Engineer District, New York. The objective of the study was to investigate the impact of a potential storm surge barrier on the Hackensack River, New Jersey, just upstream of its confluence with the Passaic River, on flood control in the two river basins. The model has been applied by WES to Bolsa Chica Bay, California, (Hales et al. 1989) to study the impacts of opening a new entrance and flooding wetlands on hydrodynamics and water quality. An improved fully two-dimensional version of this model has recently been used in storm surge analysis of the Passaic River Flood Protection Project (Demirbilek and Walton 1992).

(4) Bibliography. For additional information, refer to Moore and Walton (1984), GKY and Associates (1988a, 1988b), and Demirbilek and Walton (1992).

d. Two-dimensional vertically averaged models. These models neglect vertical accelerations and velocities and integrate the 3-D equations of motion in the vertical

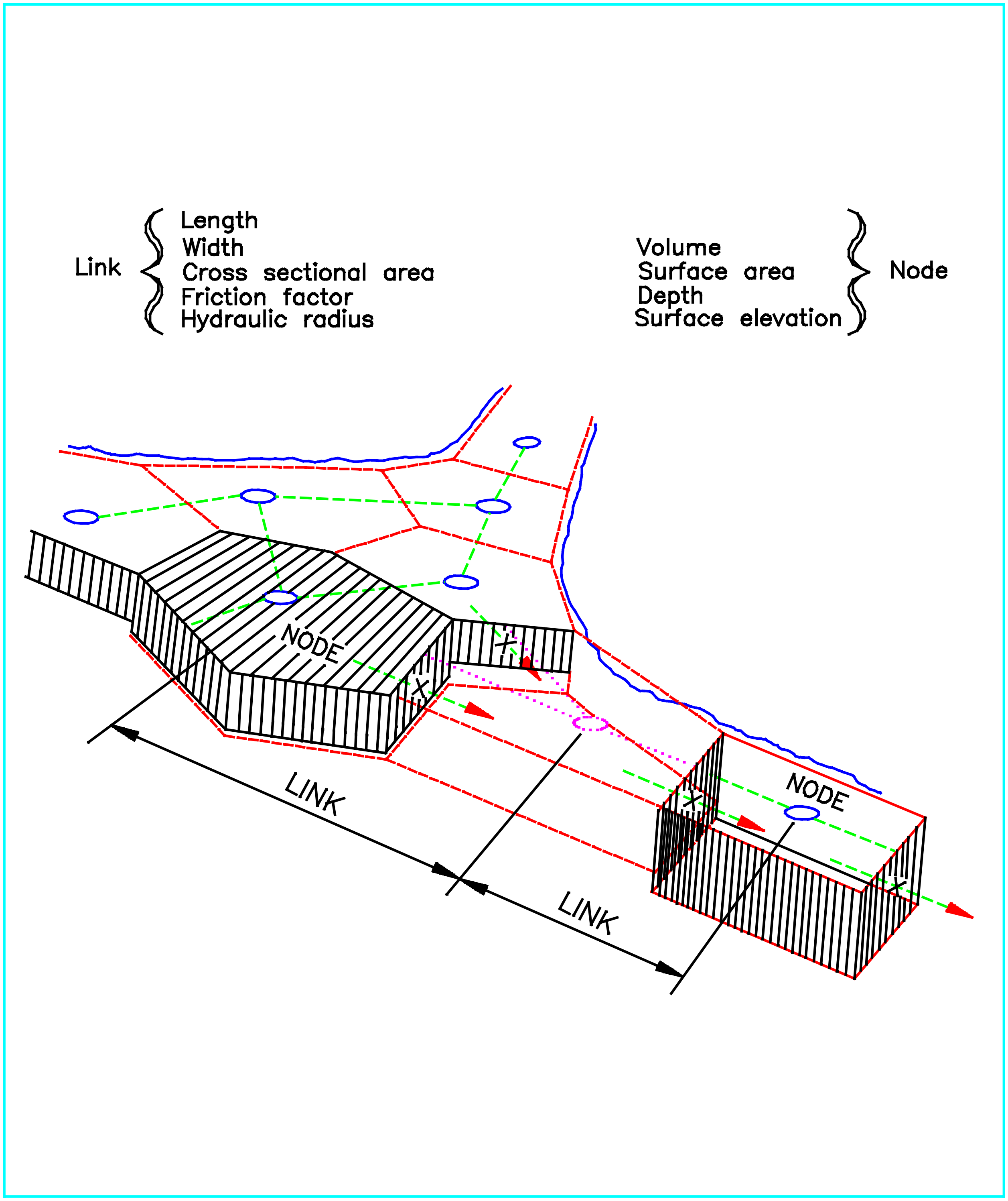

Figure 7-2. Pseudo-two-dimensional geometric representation for inlet systems

direction. They predict surface elevations and vertically averaged velocities. An example of this type is the WES Implicit Flooding Model (WIFM).

(1) Description. The WIFM is a finite difference model that uses an alternating-direction-implicit (ADI) solution scheme. It has been applied successfully to a variety of Corps shallow-water wave studies involving response to tides, winds, storm surge, and tsunamis. The model can be applied on a variable rectilinear grid, and accounts for advection and Coriolis terms. It can simulate flooding and drying of low-lying areas, and represent the effects of sub-grid scale barriers such as jetties and breakwaters. The WIFM has a "hot-start" feature, which enables simulations to be continued from results of a previous computer run. The WIFM can be accessed through the Coastal Modeling System (CMS) (Cialone et al. 1991).

(2) Model requirements. Essential input required to run WIFM consists of the following: bathymetric and geometric information for the ocean-inlet-bay system, numerical grid characteristics, information on structures (length, height, overtopping or not, discharge coefficients), friction factors for the region, time histories of surface elevations and discharges at the grid boundaries, and time history of winds (spatial and time variation of speed and direction). In the case of tides, tidal constituent information can be used instead of measured tidal levels at the boundaries. To calibrate and verify the model, measured velocities and elevations at select locations in the interior of the grid are required. Typical output consists of snapshots of elevations and velocities over the whole grid at selected instants of time during the simulation, time histories of velocity and elevation at selected cell locations ("gauges") throughout the simulation, and variation with time of discharge across selected ranges (flow openings). This information can be used during post-processing to obtain snapshot vector plots and time series plots.

(3) Example applications. The WIFM has been applied to the following inlets: Oregon Inlet, North Carolina, to study the effect of jetty spacing and channel stabilization on tides and storm surge; St. Marys Inlet, Florida, to determine the effects of channel modification and jetty sealing on tidal circulation near a jettied inlet; Yaquina Bay, Oregon, to determine tidal currents near the jetties and provide guidance for jetty rehabilitation; and Los Angeles-Long Beach Harbors, California, to determine the effects of proposed plans on tidal circulation and flushing.

(4) Bibliography. Additional information is provided in Butler (1978a,b,c; 1980); Leenknecht, Earickson, and Butler (1984); Seabergh (1985); Cialone (1986); Vemulakonda et al. (1988); and Cialone et al. (1991). WIFM is available to Corps personnel via the CMS on the CRAY Y-MP supercomputer that resides at the Information Technology Laboratory (ITL), U.S. Army Engineer Waterways Experiment Station (WES) (Cialone et al. 1991).

e. Three-dimensional models. These models solve the full three-dimensional equations of motion to obtain surface elevation and the three components of velocity, as well as the vertical variation of velocity. An example of this type is the CH3D model.

(1) Description. The CH3D determines the response of coastal currents and surface elevation to the action of tides, wind, and density gradients. The model includes Coriolis effects, advection, and horizontal and vertical turbulent mixing. In addition to hydrodynamics, the model permits computation of temperature and salinity. A second-order closure model is available to characterize turbulent transport. The CH3D is a finite difference model and permits a variable rectilinear grid in the horizontal, just like WIFM. In the vertical, a sigma stretching transformation, which allows the same number of grid layers in the shallow and deep waters, is used. As a result, the bottom is represented smoothly and the order of vertical resolution is kept constant throughout the grid. The model uses an efficient mode-splitting technique of solution. The model also permits use of a nonorthogonal boundary-fitted coordinate grid in the horizontal and/or layered (z-plane) vertical treatment. In this procedure, the external mode, which is represented by the vertically integrated equations of motion, is first solved by an alternating direction, implicit method, similar to WIFM. As a result, values of the free surface elevation and vertically averaged velocities throughout the grid are known. The model then solves the internal mode, which represents the deviation of the three-dimensional velocity field from the external mode. When the results for the two modes are combined, the full 3-D solution is obtained.

(2) Model requirements. In addition to the type of input required for WIFM, the model input consists of choices for computing bottom friction, advection terms, and lateral turbulence. Because the model solves the equations of motion in a dimensionless form, certain reference values needed to make variables dimensionless must be furnished. In addition, information on initial

values of temperature and salinity throughout the grid as well as boundary information throughout the simulation period must be provided, if these variables are to be modeled. Boundary information is needed not only at the lateral and bottom boundaries but also at the free surface. Model output consists of printouts at selected times of surface elevation, velocity fluxes in x and y directions, the three velocity components, temperature and salinity at different vertical levels over the whole grid, as well as time series of the same variables at selected gauge locations. Tide-induced residual currents also can be computed. Instead of numerical values being printed, printer plots of contours of the variables at selected instants of time over the whole grid may be obtained. Results may be stored in computer files and used for post-processing, such as for vector and time series plots and plots of velocity fields within a vertical transect across entrances.

(3) Example applications. The CH3D has been applied to determine tide and wind-driven circulation over Mississippi Sound (Sheng 1983) and, in a modified form, to compute tidal and wind-induced circulation over Los Angeles-Long Beach Harbors under existing and planned conditions (Coastal Engineering Research Center 1990; Vemulakonda, Chou, and Hall 1991).

(4) Bibliography. Additional information can be found in Sheng (1983, 1984) and Johnson et al. (1991a, 1991b).

7-4. Short-Period Wave Models

a. RCPWAVE. The Regional Coastal Process Wave (RCPWAVE) model is a monochromatic short-period wave model that employs a significant wave approach and linear wave theory.

(1) Description. The RCPWAVE (Ebersole, Cialone, and Prater 1986) is a finite difference model and allows the use of a variable rectilinear grid. It takes wave conditions in deeper water (typically 18.3-m (60-ft) depth or so) where the bottom contours are reasonably shore-parallel and where the waves have been subject only to shoaling and refraction, and propagates the waves towards the shore where most of the engineering applications are. It is assumed that Snell's law is valid from the offshore boundary of the model grid to deep water. The model computes the effects of refraction and depth diffraction. Structure diffraction may be taken into account approximately by a separate program which employs the Penney and Price (1952) solution near structures. The RCPWAVE solves a form of the "mild slope equation." It assumes that bottom slopes are small, wave reflections are negligible, and energy losses outside the surf zone are negligible. Wave breaking and subsequent wave transformation in the surf zone are modeled using the empirical method of Dally, Dean, and Dalrymple (1984). The RCPWAVE is accessible to Corps personnel via the CMS (Cialone et al. 1991).

(2) Model requirements. In addition to information on the grid characteristics and bathymetry for the region, RCPWAVE requires wave characteristics in deep water (wave height, direction, and period). These may be obtained either from WIS or field data. The model computes wave conditions at the offshore boundary from this information. Model output consists of wave height, direction, and wave number at the centers of grid cells. Also available is information on breaker location.

(3) Example applications. The RCPWAVE has been applied to numerous Corps projects by CERC and Corps Districts. These include Oregon Inlet, North Carolina; St. Marys Inlet, Florida; and Yaquina Bay, Oregon. Model simulations have been used for a variety of purposes, including design of structures, determination of wave-induced currents, and sediment transport calculations.

(4) Bibliography. For additional information, refer to Ebersole (1985), Cialone (1986); Ebersole, Cialone, and Prater (1986); Vemulakonda et al. (1988); and Cialone et al. (1991). RCPWAVE is available to Corps personnel via the CMS (Cialone et al. 1991).

b. HARBD. This model determines oscillations in harbors and water wave scattering in a region consisting of arbitrary boundaries, having variable bathymetry, and forced by ocean waves at an arbitrary depth (shallow, intermediate, or deep) (Chen and Houston 1987).

(1) Description. HARBD is a finite element model applicable to linear water waves. It permits fixed floating platforms in the region considered. The model takes into account bottom friction and boundary absorption (energy loss due to wave reflection). HARBD uses a hybrid finite element method based on a variational principle for numerical solution. The model does not account for wave breaking and transformation in the surf zone and in its present form does not predict wave direction.

(2) Model requirements. In addition to information on the finite element grid (such as identification of nodes, their coordinates, and elements and their correspondence with nodes) and bathymetry, input required consists of

friction coefficients of elements, reflection coefficients of boundary elements, and angle and period of incident waves. Because the models are linear, the input (forcing) wave amplitude is assumed to be unity for convenience. Model output consists of the absolute value and phase of the normalized nodal potential at the nodes of the grid. The absolute value represents the wave amplification factor (ratio of local wave height at that particular node to the incident wave) so the local wave height can be computed. Model output averaged over a basin (a basin is defined as an area consisting of one or more elements) can be printed for several basins specified in the input. For additional information on input and output, refer to Chen and Houston (1987).

(3) Example applications. The HARBD model has been applied to harbor response studies for Fisherman's Wharf, San Francisco, California; Indiana Harbor, Indiana; Green Harbor, Massachusetts; and Agat, Guam.

(4) Bibliography. Additional information may be found in Bottin, Sargent, and Mize (1985); Weishar (1988); Chen and Houston (1987); Clausner and Abel (1987); and Crawford and Chen (1988). HARBD is available within the CMS (Cialone et al. 1991).

c. REF/DIF. The numerical model REF/DIF is a monochromatic combined refraction/diffraction model that can account for wave-current interactions. The program calculates the forward scattered wave field in regions with slowly varying depth and current, including the effects of refraction and diffraction.

(1) Description. REF/DIF is based on Booij's (1981) parabolic approximation for Berkoff's (1972) mild slope equation, where reflected waves are neglected. The model is valid for waves propagating within 60 deg of the input direction. REF/DIF is based on Stokes perturbation expansion. In order to have a model that is valid in shallow water outside the Stokes range of validity, a dispersion relationship which accounts for the nonlinear effects of amplitude (Hedges 1976) is provided. The model may be operated in three different modes (1) linear, (2) Stokes-to-Hedges nonlinear model, and (3) Stokes weakly nonlinear. Wave breaking is based on Kirby and Dalrymple's (1986) dissipation scheme, which is initiated when the wave breaker index is exceeded. Land boundaries such as coastlines and islands are modeled using the thin film approximation where the surface piercing feature is replaced by shoals with very shallow depth.

(2) Model requirements. REF/DIF requires a depth grid representing the region of interest, as well as information about the wave (height, period, and direction), and water level (surge, tide) time history at the offshore boundary of the model grid.

(3) Example applications. REF/DIF has been applied to Indian River Inlet, Delaware, and Kings Bay, Georgia.

(4) Bibliography. Kirby and Dalrymple (1986) and Dalrymple, Kirby, and Hwang (1984) describe REF/DIF and its application.

7-5. Wave-Induced Current Models

a. WICM. The Wave-Induced Current Model (WICM) is a two-dimensional, depth-averaged model for computing wave-induced circulation and water surface setup. The following summary was abbreviated from Chapter 14 of the CMS Manual (Cialone et al. 1991).

(1) Description. WICM solves finite difference approximations of the Navier-Stokes (continuity and horizontal momentum) equations for the water surface displacement and the unit flow rate components. Because WICM is two-dimensional, velocities are treated as depth-averaged quantities (i.e., velocities are constant in magnitude and direction over depth). WICM can simulate flow fields induced by wave fields, wind fields, river inflows/outflows, and tidal forcing. This finite difference model is developed in boundary-fitted (curvilinear) coordinates.

(2) Model requirements. The types of data processed by WICM are extensive and encompass a wide range of possible applications. Since each application is unique, the type of input data required for each study will vary. In general, there are seven categories of data requirements: model control specifications (e.g., run title, units); grid description (rectilinear or curvilinear cells); physical characteristics (topography/bathymetry, bottom friction coefficients, and barriers influencing tidal circulation and storm surge levels); boundary conditions (tidal elevation, discharge, and uniform flux condition); wind field specification (steady or nonsteady); wave field specification (steady, nonuniform, monochromatic, or spectral); and output specifications.

(3) Example applications. Three illustrative examples of WICM are presented in Chapter 14 of the CMS Manual (Cialone et al. 1991). The first simulates wave breaking on a plane beach, and the other two examples discuss application of WICM to Leadbetter Beach, CA.

(4) Bibliography. WICM is available via the CMS, and model documentation is provided in Chapter 14 of the CMS manual (Cialone et al. 1991).

7-6. Sediment Transport

Numerical models for coastal sediment transport may be classified into those for noncohesive sediment and those for cohesive sediments.

a. Noncohesive sediments. An example of a model for noncohesive sediment is the sediment transport model component of the Coastal and Inlet Processes (CIP) Modeling System used in some Corps studies (Vemulakonda et al. 1985, 1988). For convenience, it will be called CIPSED hereafter.

(1) Description. The CIPSED model solves for sediment transport on a variable rectilinear grid. It is a finite difference model, that computes sediment transport using the results of a wave model, tide model, and a wave-induced current model. In the past, results of RCPWAVE, WIFM, and CURRENT were used for input and CIPSED was used for long-term simulation ("average year"), excluding severe storms such as hurricanes. A time-marching approach was used. Since the details of sediment transport are not well-understood, the model takes an empirical approach. For computing sediment transport, the area of interest is divided into two regions -- the open coast region away from the inlet, and the region near the inlet. In the open coast region, for non-storm conditions, cross-shore transport due to factors other than wave-induced and tidal currents may be neglected in comparison to longshore transport. This region may be further divided into two zones, the area within the surf zone and the area outside the surf zone. Within the surf zone, wave breaking plays a dominant role. Therefore, the total longshore transport is computed from the CERC formula (*Shore Protection Manual* (SPM) 1984) and distributed across the surf zone, using a procedure suggested by Komar (1977). Beyond the surf zone, because waves are not breaking, it is the tractive force of currents that produces sediment transport. Therefore, in this zone, the method of Ackers and White (1973) is followed after appropriate modification for the presence of waves. Finally, in the region near the inlet, where tidal and wave-induced currents play a major role in transport, the modified Ackers and White method is used. Output from CIPSED consists of transport rates in the two coordinate directions at each grid cell. These are used with a continuity equation to determine the net erosion or deposition at each grid cell for the period of simulation. In general, the model is suitable for predicting sediment transport and inlet channel shoaling under long-term average wave conditions (excluding the effect of severe storms; e.g., hurricanes and northeasters) such as those given by WIS. It can predict areas of accretion and erosion in the region under consideration. Because of grid size limitations, the model cannot accurately resolve shoreline changes, which are on the order of a meter. It can qualitatively predict changes near barrier islands. It is advisable to calibrate and verify the model with field data for the project site before applying it to new project conditions.

(2) Model requirements. Apart from grid characteristics and bathymetry, model input consists of sediment diameter, density, porosity, Manning's roughness, time-step for running the model, and parameters to control the sequencing of waves, wave-induced currents and tide during time marching. Additional input consists of output files from runs of the wave, wave-induced current, and tide models consisting of wave height, direction, wave number, tidal elevation, setup, tidal and wave-induced velocity components at the centers of grid cells, and breaker location. Model output consists of sediment transport rates in two coordinate directions, and net erosion or deposition at the end of the simulation for each grid cell. Intermediate results and a mass conservation check are also printed at desired time intervals.

(3) Example applications. An earlier version of CIPSED was used for the Oregon Inlet, North Carolina, project (Vemulakonda et al. 1985) to evaluate erosion and accretion in the ocean bar entrance channel and the lateral movement of the channel when just the south jetty was in place. This single jetty case simulated a construction sequence in which the south jetty was built before the beginning of construction of the north jetty. The model was used for St. Marys Inlet (Kings Bay Study) (Vemulakonda et al. 1988) to study channel shoaling under existing and plan conditions, and recommend advance maintenance dredging for different reaches of the channel for plan conditions.

(4) Bibliography. For additional information, refer to Vemulakonda and Scheffner (1987) and Vemulakonda, Houston, and Swain (1989).

b. Models for cohesive sediments. An example of an algorithm that has been applied to predict cohesive sediment transport resuspension is documented by Cialone et al. (1991). Note that this module does not predict sediment transport rates or directions, only the potential for sediment to suspend in the water column.

(1) Description. For the Green Bay, Wisconsin, study, the potential for cohesive sediment resuspension in the Bay was evaluated using output from the three-dimensional velocity model, CH3D, to drive a cohesive sediment resuspension module. The module was developed for shallow water based on sediment resuspension being a function of the orbital velocities associated with short wave fields, together with the shear stress imparted by the depth-averaged flow (output from CH3D). To account for this coupled process, an effective increase in the bed shear stress was used in the algorithm. A relationship developed by Bijker (1967) was used, which states that an effective shear stress reflecting both waves and currents can be written as a function of a wave-induced increase in the bed shear stress produced by currents only.

(2) Module requirements. The cohesive sediment resuspension module requires output from CH3D (root-mean-square velocities at each grid cell), as well as wave orbital velocities. Significant wave heights and periods were estimated using fetch-limited shallow-water hindcasting procedures as discussed in the *Shore Protection Manual* (SPM 1984), using measured maximum sustained wind speeds.

(3) Example applications. To evaluate potential sediment resuspension patterns over a wide range of hydrodynamic conditions, the module was applied to ten scenarios at Green Bay, Wisconsin (Mark et al. 1993).

(4) Bibliography. For a discussion of the module's development and application to Green Bay, Wisconsin, see Mark et al. (1993).

7-7. Numerical Modeling Systems

Apart from individual numerical models, numerical modeling systems containing a suite of numerical models (for example, models for tides, waves, wave-induced currents, and sediment transport) may be employed for studies on coastal hydraulics and sedimentation. There are several advantages to such systems. For instance, all the models are of the same type (finite-difference or finite element), they use the same type of grid, information can be readily transferred from one model to another, and the individual component models of the system can be applied in different combinations, depending on the specific application. An example of a numerical modeling system for the inlet environment was the Coastal and Inlet Processes (CIP) System, applied to several Corps studies.

a. Description. The CIP System consisted of models for tide, wave, wave-induced current, and noncohesive sediment transport. All the models of the system were of the finite-difference type and were applied on a variable rectilinear grid.

b. Model requirements. Input requirements for the types of models within the CIP System have been described.

c. Example applications. The modeling system was originally developed for the Oregon Inlet project (Vemulakonda et al. 1985), and was also applied at Kings Bay (Vemulakonda et al. 1988) and Yaquina Bay (Cialone 1986).

d. Bibliography. Additional information may be found in Houston et al. (1986); Cialone and Simpson (1987); Vemulakonda and Scheffner (1987); and Vemulakonda, Houston, and Swain (1989).

7-8. Numerical Model Implementation

The following paragraphs deal with aspects of model implementation that must be considered when applying numerical models at inlets.

a. Grid characteristics. The grid typically should include the inlet, the barrier islands adjacent to the inlet, the back bay, and a portion of the ocean area in front of the inlet. The grid boundaries must be located sufficiently far away from the inlet so the boundary conditions are not affected by planned changes near the inlet. Boundary locations must be chosen carefully so the flow satisfies the boundary conditions. Depending on the process modeled, the grid cells must be sufficiently fine near the inlet, the navigation channels, the back bay, and the surf zone for proper representation. Grid cells can be coarse near the lateral and offshore boundaries. In tidal and wave-induced current models, the grid cell size, depth, and expected maximum local velocity dictate the maximum time-step that can be used for simulation. Computational time and storage typically depend on some power (greater than one) of the number of grid cells. Therefore, it is desirable to minimize the total number of cells, consistent with accuracy and resolution desired. This objective is achieved by using a variable rectilinear grid.

b. Grid generation.

(1) Finite difference. A variable or uniform rectilinear grid for the region of interest can be obtained, plotted,

and listed to file by using a special interactive program called CMSGRID, which is part of the CMS (Cialone et al. 1991). Output from the program consists of grid coefficients, for different regions of the grid, in the two coordinate directions. Other preprocessing programs of the CMS can use this information to determine coordinates of grid cells as well as plot the grid to any desired scale. The grid plotted to an appropriate scale is overlaid on a bathymetric chart and the depths for different grid cells are determined.

(2) Finite element. The finite element grid for the HARBD model is created manually by selecting the nodes and elements of the grid as desired. The nodes and elements are numbered in some convenient fashion and the correspondence between the nodes and elements is established. The grid is overlaid on a bathymetric chart and the coordinates of the nodes and depths are digitized. It may be necessary to modify the grid on the basis of preliminary testing.

(3) Boundary-fitted. Nonorthogonal curvilinear (boundary-fitted) grids can be made to conform to bathymetric features and provide an accurate means of representing a study area. These grids can be generated using a numerical grid generator such as program EAGLE (Thompson 1985), which has the flexibility to concentrate grid lines in shallow-deep areas or in areas where the bathymetric gradients are great.

c. Calibration/verification. Before most numerical models are applied to determine the impact of some new plan conditions, it is necessary to ensure that they reproduce the prototype behavior corresponding to some known conditions. This is the objective of the calibration/verification process. For this purpose, ideally, two complete and independent sets of prototype data are necessary. The data should include all the information necessary to run the model and check model results. Thus information on boundary conditions, forcing mechanisms, and measurements in the interior of the model grid are needed. During calibration, the model is run to correspond to the first set of conditions. Model parameters such as friction and eddy coefficients are varied until the model reproduces the prototype measurements in the interior satisfactorily. Next, the model is run in the verification mode, using the second set of conditions. During this phase, model parameters are not changed but kept at their values corresponding to calibration. Model results are compared to prototype measurements. There should be good agreement. If measured and predicted data significantly differ, the model should be re-calibrated and verified with the new calibration parameters. In practice, prototype data of the quality needed for calibration and verification are not available unless they are collected as a part of the numerical modeling project. There may be only one data set, in which case calibration/verification is done as a one-step process. Another problem encountered is that the prototype data may not be complete and accurate. In such situations, the modeler looks for qualitative agreement between model and prototype in terms of overall behavior patterns and for reasonable explanations as to why the two might differ. Once calibration and verification are successful, the model is ready for application to plan conditions. Finally, it should be noted that model calibration and verification are essential for models of tidal hydrodynamics and sediment transport. For models of waves and wave-induced currents, model calibration and verification are desirable but not essential, because understanding of the hydrodynamics of the latter phenomenon is more complete and the models have fewer site-dependent calibration parameters.

7-9. Design Use of Model Results

Typically, models may be employed to improve our understanding of various phenomena at prototype locations and to furnish explanations for observed behavior or failure. They are often used to compare existing (base) conditions to future plan conditions and thereby predict the impact of plans on hydrodynamics (velocities, discharges, water levels), water quality, and sediment transport at key locations. By testing alternate plans in the numerical models, it is possible to assess the advantages and disadvantages of each and choose from among the alternatives the best for project implementation. It may be necessary to ensure that for the design selected, velocities in the interior are adequate for mixing and flushing, velocities and waves near the navigation channel do not adversely impact navigation, and velocities near structures are sufficiently low to prevent scour. Examples of such projects are navigation channel modifications and jetty construction for channel stabilization. Often, the designer is faced with conflicting requirements. For example, by increasing jetty spacing, velocities in the navigation channel may be reduced, thereby improving navigation but worsening channel shoaling, and vice versa. Model results enable the designer to strike a balance. In light of model testing, improved designs and modifications to original designs can result. One area where significant cost reductions may be possible is in estimating maintenance dredging required after channel modifications. Using model predictions of advance maintenance dredging required for different reaches of channel, it is possible to modify the channel design and reduce the overall dredging required. Even though they are approximate, numerical models are the only tools available to predict sediment transport quantitatively in such cases.